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A HANDLING QUALITIES THEORY FOR PRECISE FLIGHT PATH CONTROL

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FOREWORD

This report was prepared for the Air Force Flight Dynamics Laboratory, Research and Technology Division, as part of Project No. 8219, Task No. 821905. It was prepared by Mr. W. Bihrle, Jr., Wantagh, Long Island, New York under USAF Contract No. 33 (615)-3199 Request No. 3. The Air Force project officer was Flight Lieutenant T. M. Harris, RCAF.

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This technical report has been reviewed and is approved.

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ABSTRACT

This paper discusses the overall subject of precise flight path control. A unifying precision control theory is presented and a control anticipation parameter is developed which relates the quantities that are involved in the man-machine precision control mechanism. A critical value for this parameter is suggested, based on experimental results, and is discussed in relation to pilot adaptability as reflected under the topics of control technique (control pumping), control function and control task. Also, an associated criterion in terms of aircraft characteristics is developed and techniques for improving the precision controllability of inherently deficient airframes through stick force and automatic flight control systems are discussed. Finally, experimental and analytical investigations are recommended which are deemed necessary for specifying the longitudinal handling qualities of manned vehicles.

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SYMBOLS

$\bar{c}$	mean aerodynamic chord, ft.
l_t	tail arm, 0.25 $\bar{c}$ of tail to 0.25 $\bar{c}$ of wing
S	wing area, ft.^{2}
W	weight, pound
ρ	mass density of air, slug/cu.ft.
I_Y	moment of inertia in pitch, slug-ft.^{2}
n_{ss}	steady state load factor
n_α	load factor per unit of angle of attack
C.G.	center of gravity
g	gravitational constant
V	velocity, ft./sec.
q	dynamic pressure, lb./ft.^{2}
α	angle of attack
θ	angle of pitch
γ	flight path angle
δ	horizontal control surface deflection
C_L	lift coefficient, lift/qS
C_{L_α}	lift curve slope, $\dfrac{\partial C_L}{\partial \alpha}$
C_{L_δ}	control effectiveness, $\dfrac{\partial C_L}{\partial \delta}$
C_m	pitching moment coefficient, moment/qS$\bar{c}$
$C_{m_{C_L}}$	static margin derivative, $\dfrac{\partial C_m}{\partial C_L}$

C_{m_δ}	control power, $\dfrac{\partial C_m}{\partial \delta}$
$C_{m_{\dot{\theta}}}$	damping derivative, $\dfrac{\partial C_m}{\partial \frac{\dot{\theta}\bar{c}}{2V}}$
C_{m_α}	static stability derivative, $\dfrac{\partial C_m}{\partial \alpha}$
$C_{m_{\dot{\alpha}}}$	damping derivative, $\dfrac{\partial C_m}{\partial \frac{\dot{\alpha}\bar{c}}{2V}}$
ω_n	undamped natural frequency
ω	angular frequency of forcing function, radians/sec.
ζ	damping ratio
$1/T$	corner frequency, radians/sec.
K	gain, steady state ratio of the output to input
P	differential operator, $\partial/\partial t$
$\left\lvert\dfrac{\ddot{\theta}}{\delta}\right\rvert, \left\lvert\dfrac{\dot{\theta}}{\delta}\right\rvert, \left\lvert\dfrac{\dot{\delta}}{\delta}\right\rvert$	amplitude ratio of indicated output to indicated input, per sec.^{2}, per sec., and per sec., respectively
Φ	phase angle between indicated output and input
db	decibel

NOTE: 1) Dots over symbols represent derivatives with respect to time.
2) Δ , incremental, measured from 1g trim.
3) Subscript o denotes initial condition.

SECTION I

INTRODUCTION

It has been recognized for the last decade that the ability of a pilot to perform precise flight path tasks is a function of the inherent short period dynamic characteristics (ω_n and ζ) of the controlled vehicle. Numerous flight and simulator investigations have, therefore, been conducted to determine the short period dynamic characteristics which identify iso-opinion lines of desirable, acceptable and unacceptable longitudinal handling qualities. During these investigations, it has been observed that the iso-opinion lines could be appreciably displaced or appear to be inapplicable relative to different classes of aircraft (variable stability, research, military fighters and commercial transports). Also, fixed base simulator studies would establish iso-opinion lines that were displaced from those obtained during a flying vehicle investigation.

A hypothesis had been presented some years ago (References (1) and (2)) which attempted to explain the mechanism involved in the man-machine precision control task. At the time, the hypothesis satisfactorily explained and predicted all known precise control problems and has continued to serve that function relative to the apparent inconsistancies that have been observed during control, landing approach and handling quality research investigations to date.

It is the intent of this paper to discuss the overall subject of precise flight path control, to present a unifying control theory which describes the man-machine controlling mechanism and to present an associated criterion for specifying the aircraft characteristics required for the performance of precision flight path tasks.

SECTION II

PRECISION CONTROL THEORY

A. BACKGROUND

Cornell Aeronautical Laboratory has repeatedly demonstrated the correlation between the ability of a pilot to perform efficiently as a flight path controller and the characteristics (ω_n , ζ) or the coefficients ($2\zeta\omega_n$, ω_n^2) which describe a second order system (see References (3) and (4)). It should be realized, however, that these second order system characteristics are not the ingredients, per se, which are directly involved in the man-machine controlling mechanism. It would be suspected, however, (because of the overall correlation shown to date) that the aerodynamic and physical characteristics which are most influential in determining the magnitude of ζ and ω_n are directly involved in the controlling task.

B. THE PROBLEM

The precision control problem can best be described by referring to the pilot comments that are obtained during a handling qualities research investigation or weapon system flight test program.

For instance, the pilot commented in Reference (4) that at low airplane frequencies the airplane was slow and sluggish and that he must overdrive it to obtain satisfactory pitch response. It also became difficult to judge the input required to command a response after overdriving it to get it started.

The same type of pilot comments may be obtained during the normal course of a flight test program in which the contractor establishes the limit of the aft center of gravity location. As the center of gravity moves aft, the aircraft becomes difficult to fly in formation. The aircraft is crabbed for control lag and for overshooting the desired load factor.

It should be noted that as far as the airplane response in normal acceleration is concerned, aft movement of the center of gravity results in an increase in normal acceleration per unit stick deflection. The damping ratio, and with it the percent overshoot, are also improved by aft movement of the center of gravity. The pilot's subjective opinion to the contrary, however, is taken to be correct and must be explained.

C. DEVELOPMENT OF THEORY

The above noted formation flying difficulty is basically a problem in the precise control of the flight path. In order to make precise adjustments to the flight path, the pilot must be able to anticipate the ultimate response of the airplane. It is established in the Appendix and hypothesized in References (5) and (6)that angular pitching acceleration is used for this purpose.

When the pilot moves the longitudinal control, he applies a pitching moment to the airplane. The pitching moment instantaneously produces a proportional angular pitching acceleration. The instantaneous angular pitching acceleration experienced by the airplane in response to a unit application of control is:

$$\ddot{\theta}_o = \frac{q\,S\,\bar{c} \quad C_{m_\delta}\,\Delta\delta}{I_Y} \qquad \text{Eq. (1)}$$

The ultimate result would be that the airplane pitches to some steady state angle of attack and corresponding load factor, defined by the equation:

$$\Delta n_{ss} = \frac{-\left[1 + \dfrac{C_{m_{C_L}}}{l_t/\bar{c}}\right] C_{m_\delta}\,\Delta\delta}{C_{m_{C_L}} \quad C_L + \dfrac{\bar{c}g}{2V^2}\,C_{m_{\dot{\theta}}}} \qquad \text{Eq. (2)}$$

Figure 1 presents the response in normal and angular acceleration to a step input of the longitudinal control for two different aircraft. The magnitude of the control deflection is, in each case, just the amount necessary to pull an incremental 1 g of steady state normal acceleration. The amount of time by which the angular acceleration precedes (leads) the normal acceleration can be readily seen.

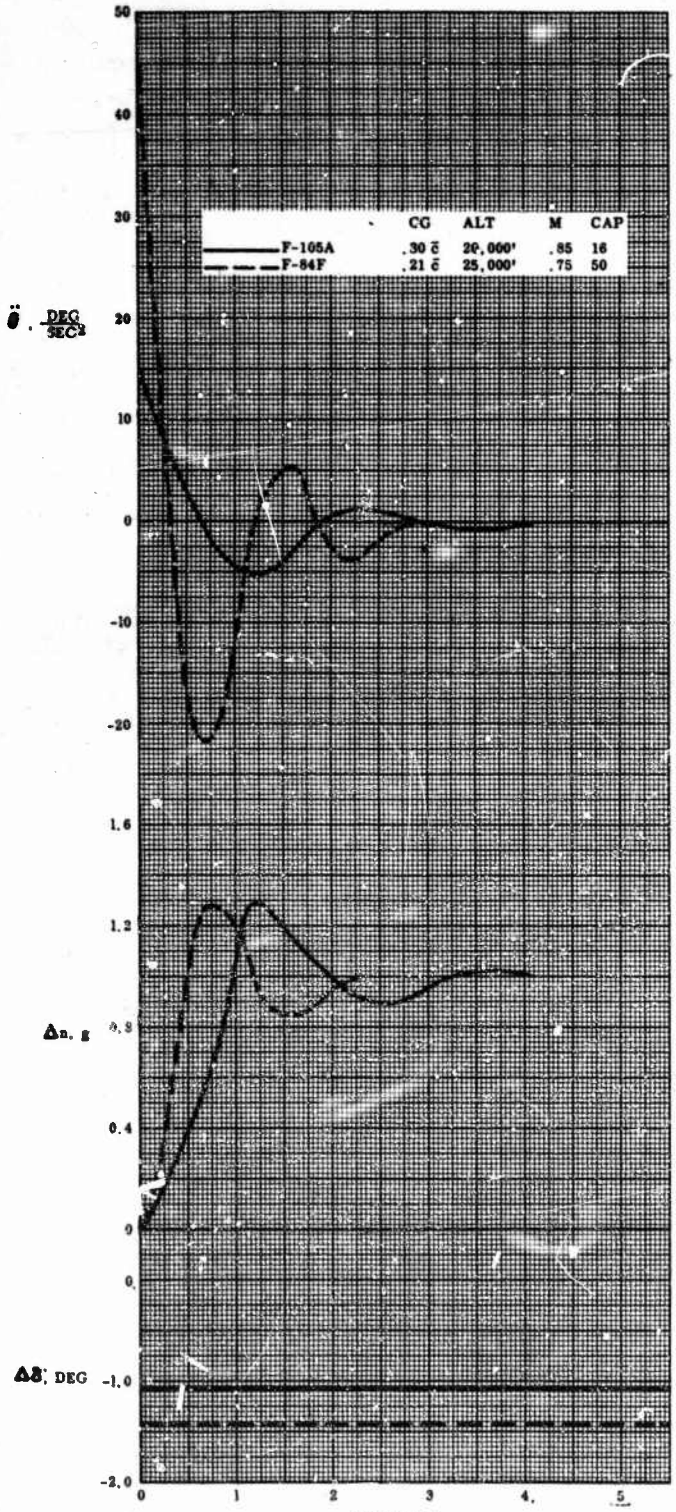

Fig. 1 A COMPARISON OF THE RESPONSE OF TWO AIRCRAFT

The present theory is that in order to make precise adjustments to the flight path, the pilot must be able to anticipate the ultimate response of the airplane. He gets a perceptible anticipation signal in the pitching acceleration. For airplanes having high inertia or low static stability, the angular pitching acceleration accompanying small adjustments to the flight path may fall below the threshold of perception.(1) Such airplanes are difficult to fly during a maneuver which requires precise flight path adjustment. The amount of instantaneous angular pitching acceleration per unit of steady state normal acceleration is, therefore, an index of the strength of the anticipation signal received by the pilot. This quantity, called the control anticipation parameter (CAP), will be used as a measure of the flying quality of an aircraft. For the characteristics shown in Figure 1, the high value of the CAP (50 degrees per second squared per g) corresponds to an airplane which is judged good in formation flying. The low value of the CAP (16 degrees per second squared per g) corresponds to the case for which adverse comments were noted relative to formation flying characteristics.

If Eq. (1) is divided by Eq. (2), the resulting ratio is the CAP.

$$\text{CAP} = \frac{\ddot{\theta}_o}{\Delta n_{ss}} = \frac{W\bar{c}\, C_{m_{C_L}} + \frac{1}{4} S\bar{c}^{\,2} \rho\, g\, C_{m_{\dot{\theta}}}}{-I_Y \left[1 + \frac{C_{m_{C_L}}}{l_t/\bar{c}} \right]} \qquad \text{Eq. (3)}$$

It can be seen that the most important terms are the maneuver margin, static margin and the vehicle dimensions. In fact, the CAP is a reflection of the basic airframe characteristics and is, unfortunately, not easily adjusted.

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(1) It is indicated in Reference (7) that the threshold value is a function of the time duration the angular acceleration is acting on the subject. Unfortunately, no value is available in this reference material for the short time periods encountered during precision tasks. The control pumping analysis presented in the Appendix indicates, however, that this threshold value is of the order of 6.5 degrees per second squared and this value has been experimentally substantiated (6.88 degrees per second squared being the mean measured value) in Reference (8).

Satisfactory airplane controllability would be bracketed by a lower and upper limit of this control anticipation parameter. The above example defines the lower limit which, for a given control task, should be a singular number since it is based on a physiological limitation of man. The upper limit would be indicative of a horrendous anticipatory signal for a relatively small flight path correction. This upper limit may be a band of values since the acceptability in this instance would be subjective.

D. INTERPRETATION OF PILOT COMMENTS

If an airplane has too small a control anticipatory characteristic (which is a function of the task and is discussed in Section III B), the pilot will have a legitimate comment to the effect that the pitch response is sluggish, there is a control lag, the aircraft is not closely coupled and he overshoots or overdrives the airplane. In light of the CAP theory, his comments are based on the following experience. When the flight path requires adjustment, he moves the control and his vestibular organ detects no angular pitching acceleration. The absence of this anticipatory cue leads him to doubt the response of the airplane and to consequently increase the control deflection until a perceptible level of pitching acceleration is attained. This control deflection, of course, is finally accompanied by a large change in normal acceleration and a resultant "overshooting" or "overdriving" of the airplane. In attempting to correct this self-induced flight path error, the above experience is again encountered and a pilot induced oscillation (P.I.O.) can result.

An airplane having an over-adequate anticipatory characteristic will result in pilot comments such as: The initial response is fast and abrupt, too sensitive, too closely coupled, moves in steps and has a tendency to P.I.O. In this instance, the pilot experiences a very high level of anticipatory cue for the small steady state flight path correction desired and thereby immediately limits or partially retracts his control input. The resulting control deflection, however, falls short of producing the desired flight path correction. His action is then repeated with the same sequence of events. The result is that the pilot either approaches a correction in flight path in incremental steps or enters a P.I.O. maneuver.

The following situation was also realized during the acceptance tests of a fixed base mission trainer as witnessed by the author and observed in Reference (5). The subjective opinion, of knowledgeable pilots, that the trainer is simulating the handling qualities of the flying article is only realized when the response (short period) characteristics of the trainer are adjusted to completely unrealistic (highly damped) values. Apparantly, the fixed base trainer, which faithfully represents the dynamic response characteristics of the flying article,

is more difficult to fly than the aircraft. For this reason, different iso-opinion lines are also obtained during research investigations employing a fixed base simulator and a flying vehicle (see, for example, Reference (6)). The use of a fixed base simulator obviously removes, what is proposed herein as, the main anticipatory cue (angular acceleration) employed during a tight control task.

Many additional examples can be given in which the pilot comments or actions can be readily explained on the basis of the CAP theory.

SECTION III

CRITICAL VALUE FOR THE CONTROL ANTICIPATION PARAMETER

A. DEFINITION

The main objective of all handling quality criteria is to be able to clearly identify the physical system characteristics which prevent the pilot from "flying" the aircraft in a safe and efficient manner. An iso-opinion line or index value which can consistently perform this function for many type vehicles is a verification of the basic correctness and applicability of the criterion. The critical value for the control anticipation parameter is defined herein as the value at which the pilot

(1) is completely unable to perform his task

or

(2) is required to change his control technique or control function

Complete frustration on the part of the pilot in attempting to perform an assigned precision control task is easily recognized by all concerned. Formation flying, inflight refueling, tracking and landing are tasks which involve precision control of the flight path. Formation flying probably requires the most control preciseness. Since the critical value is in itself a function of the severity (demands on the man-machine combination) of the control task, a value which is established during a formation flying task would be proper since all other precision tasks could then be performed acceptably.

The second condition is placed on the above definition because of the adaptability of the human pilot. It is recognized that performance of a task cannot be used as an index of the handling qualities of an aircraft because of this desirable human characteristic. Investigators have, therefore, in the past resorted to interrogation of the pilot relative to the skill, effort, etc., required to perform the task. It is possible, however, as discussed below, to observe the adaptability of the pilot and, therefore, to use another technique for establishing the critical controllability value.

B. SIGNIFICANCE OF PILOT ADAPTABILITY

When the inherent aircraft controllability parameter falls below the critical value, the pilot cannot perform the task or the pilot's adaptability may be reflected in the subconscious selection of a different control technique or control function. This effect can be illustrated for the landing task.

1. Control Technique

The desire to be a tight controller (high gain) in the man-machine loop is only realized when the consequence of performing poorly is disastrous and/or when the task itself demands a very high level of precision. Consequently, if a landing is being conducted with an aircraft which falls below the critical controllability value, the pilot may resort to pumping the control (change in his normal control technique) for the reasons discussed in the following paragraph. The point to be made here is that in no instance will the pilot pump the control when shooting practice landings on a cloud and he usually will not start his control pumping action during an actual landing until the final phase (terminal conditions) is approached.

It is shown in the Appendix that the pilot pumps the control at a predictable frequency and amplitude above the natural frequency of the aircraft. In this manner the pilot could become a high gain element in the man-machine control loop without driving the system unstable (P.I.O.). This is accomplished by pumping at a frequency which generates the maximum achievable angular acceleration response with the minimum attainable phase shift between this quantity and the control forcing function (see Figure A-2, Page 24). It is also shown in the Appendix that this high pumping frequency barely excites $\dot{\gamma}$ (see Figure A-4, Page 26) and thereby an insignificant change in flight path is realized. It is deduced, therefore, that this control technique permits the pilot to establish command (assurance) since he is able to continually sample the high gain responsiveness of the man-machine combination and, at the same time, achieve fine vernier type control of the flight attitude angle and path by moving the base line of the control pumping action.

2. Control Function

When the controllability parameter is below the critical value, the pilot may select to modify his control function rather than his control technique. This subconscious choice is predictable, to some extent, for the landing task on the basis of the control function normally required of the pilot during the other portions of the mission (which is a function of the aircraft classification). For instance, it has been observed by the author that, when a group of bomber pilots were transferred to tactical fighter aircraft, the aircraft were landed without any noticeable control pumping action. After approximately two weeks of operational flying, these same pilots had unknowingly become control pumpers. It may be that a fighter pilot is "flying" an aircraft in the sense that he is an integral part of the vehicle and the machine is an extension of his capabilities. This is his control technique during formation flight, tracking and inflight refueling tasks. On the other hand, much of the mission time of a commercial

jet transport or strategic bomber pilot is relegated to controlling tasks which involve monitoring, initiation of flight procedures, control of a process as a function of instrument information, etc. A pilot with this mission function background is more apt, therefore, to accept the role of basically programming control inputs (characteristic of high inertia vehicles, i.e., jet transports, submarines) to achieve a task. Also, by extensive training on procedure flight trainers and aircraft, the pilot can fulfill this role with a minimum of anxiety since he has repeatedly proven to himself that the aircraft can be landed safely in this fashion. It is not inferred that the task is less demanding when reverting to this control function mode but it does mean that the requirement for fine precision controllability has been negated to some degree. However, since the pilot is now effectively removing himself as much as possible from the precision control loop, it can be argued that the use or need for this control function requires increased pilot training and prevents the optimum usage (a consistently minimum touchdown and sink speed) of the aircraft. On this basis, it would appear desirable to supply actuator rates and stick forces which do not prevent or discourage the pilot from selecting a different control technique (i.e., pumping) in lieu of the "programmer" type control function.

In summation, the gross landing (getting landborne) task can be accomplished even though the vehicle does not possess the inherent required controllability because of the adaptability of the pilot relative to his control technique or control function. A change in control technique makes it possible to perform precision (tight) control whereas a change in control function negates, to a degree, the need for precision control.

3. Control Task

The ability to overcome or circumvent the lack of inherent vehicle precision controllability is a function of the mission, i.e., the task involved and task duration. The final phase of a landing is of short duration and the effort of control pumping is quite acceptable. In fact, because of the short duration and the high demands of the task, the pilot may, in most cases, not be aware of his actions. The pumping control technique may also be employed during formation flying, inflight refueling and tracking for aircraft lacking in precision controllability (CAP value below the lower critical value). In these instances, the acceptability of this control technique is very questionable because of the relatively increased duration of the tasks. The inadequacies of the inherent airframe are reflected in increased pilot effort and this technique is, therefore, usually considered an unacceptable substitute for a basically deficient airframe characteristic. It should also be noted, that for these tasks the control function role cannot be modified as was the case for landing. These tasks require a higher degree of precision control since the allowable tolerances in flight path control required for successful task

performance are minute relative to the overall landing task. Although the control pumping technique may be unacceptable as a substitute for controlling certain classes of deficient airframes, it can be used as a source of information for establishing the critical controllability value.

C. METHODS FOR ESTABLISHING VALUE

An approximate critical value for the control anticipation parameter can be established by reviewing past pilot comments relative to the difficulty of performing precision maneuvers and by examining available flight test records for control pumping during these tasks. This information can then be correlated with the computed value of the control anticipation parameter. This was the method that was employed for initially establishing credence in the CAP theory. The CAP value and corresponding pilot opinion that were obtained for various aircraft in the cruise airframe alone configuration while performing a formation flying task are presented below.

Airplane	Configuration	C.G. $\% \bar{c}$	CAP deg./sec.^{2}/g	Pilot Opinion Or Action
F-84F	Cruise	21	50	Good
F-101	"	28.6	40	Good
F-105B	"	23	28	Good
F-84F	"	29	23	Acceptable
F-105A	"	30	16	Poor
F-106	"	—	16	Poor
F-84F	"	33	14	Unacceptable
F-105A	Landing	34	16.1	Control Pumped
F-84E	"	26	15.8	Control Pumped
F-84F	"	30	14.4	Control Pumped

Based on these data, it appeared that good handling qualities are realized for CAP values above 25 degrees per second squared per g and that the lower critical value is approximately 15. Also listed in the above table are the CAP values for different aircraft in the landing configuration. Although the landing task is less demanding, the majority of pilots pumped the control during the landing for CAP values below 16.

Obviously, the <u>only</u> way to determine this value efficiently and accurately is to conduct a controlled systematic investigation employing a variable stability aircraft. The above described procedure can be used then to verify the validity of this experimentally determined value in that none of the past experiences (aircraft) should violate the criterion. At this point in time, the validity of the

criterion may be also demonstrated by predicting the conditions that will be considered unacceptable during the flight investigation and the amplitude and frequency of the control pumping to be experienced. Furthermore, if allowance is made for varying stick force as a function of aircraft angular acceleration during the flight investigation, it may be demonstrated that stick force cue can be substituted for the vestibular cue and permit precision tasks to be performed for airframes that are inherently lacking in controllability. The requirements for the force cues (magnitude and ratio of dynamic to steady state forces) would also thereby be established (see Section IV A).

D. EQUIVALENT SPECIFICATION CRITERIA

Although the control anticipation parameter is an index which relates the quantities which are involved in the man-machine precision control mechanism, it is desirable, if possible, to convert this index to some basic aircraft characteristic. It would then be possible to present a convenient specification which hopefully presents an iso-opinion line and allows various aircraft and flight conditions to be readily evaluated relative to their acceptability for precision control tasks.

As previously discussed, the control anticipation parameter is a ratio of

$$\frac{\ddot{\theta}_o}{\Delta n_{ss}} = \frac{W\bar{c}\, C_{m_{C_L}} + \frac{1}{4} S\bar{c}^2 \rho\, g\, C_{m_{\dot{\theta}}}}{-I_Y \left[1 + \frac{C_{m_{C_L}}}{l_t / \bar{c}} \right]} \qquad \text{Eq. (3)}$$

Also, the square of the natural frequency of the aircraft characteristic equation can be written as

$$\omega_n^2 = \frac{L_\alpha}{W} \left[\frac{W\bar{c}\, C_{m_{C_L}} + \frac{1}{4} S\bar{c}^2 \rho\, g\, C_{m_{\dot{\theta}}}}{-I_Y} \right] \qquad \text{Eq. (4)}$$

where $L_\alpha = qS\, C_{L_\alpha}$

From Equations (3) and (4) it can be seen that the CAP can be expressed as

$$CAP = \frac{W}{L_{\alpha}} \omega_n^{2} \left[\frac{1}{1 + \frac{C_{m_{C_L}}}{l_t / \bar{c}}} \right] \quad \text{Eq. (5)}$$

If one neglects $C_{m_{C_L}} \div l_t / \bar{c}$, which is normally no more that 10 to 15 percent of the denominator, and since n_{α} (load factor per unit of angle of attack) $= L_{\alpha} / W$, the CAP expression reduces to

$$CAP \approx \frac{\dot{\omega}_n^{2}}{n_{\alpha}} \quad \text{Eq. (6)}$$

SECTION IV

TECHNIQUES FOR IMPROVING THE PRECISION CONTROLLABILITY OF INHERENTLY DEFICIENT AIRFRAMES

There is a range of CAP values which are associated with good handling qualities. For this acceptable range, the pilot can perform as a tight controller since he is able to fly "by the seat of his pants" employing the cristae ampullaris and otoliths of the inner-ear to sense angular and normal accelerations, respectively. When the required CAP characteristics do not exist, proper stick force cues must be generated to assist the pilot in his controlling task and desirable dynamic control system characteristics must be achieved or the apparent airframe response characteristics must be artificially modified to permit use of the basic "seat of the pants" stimulus.

A. STICK FORCES

The use of stick force cues for attaining precision control is, in actuality, a technique for circumventing, to a limited degree, a basically deficient airframe. For example, some designers in the past have attempted to eliminate a P.I.O. tendency at a given flight condition by changing the stick-control surface gearing (mechanical advantage) ratio and, thereby, the level of stick force that is associated with an incremental change in load factor. This technique can only lead eventually to greater and greater stick forces which either effectively lock the pilot out of the control loop or become objectionable to the pilot during more gross maneuvering tasks. Since fighter aircraft pilots have shown a preference [(2)] for low stick force gradients (minimum pilot effort) during gross maneuvers, this technique is severely limited by the overall compromise required to stay within the desired gross maneuver stick forces. Also, the large dynamic pressure range and aeroelastic effects experienced by modern aircraft demand, for instance, that a correspondingly large range, continuously-variable-mechanical-advantage shifter be employed in order to obtain the required stick force cues throughout the flight regime. This type of system is normally activated as a function of Mach number and pressure altitude or dynamic pressure. The large mechanical

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(2) based on the final control forces selected by test pilots during the prototype test phase of several fighter aircraft and the extensive use of the force trim button by operational pilots during gross maneuvers

advantage range called for must be severely compromised, however, because of objectionable non-pilot-induced control surface inputs which are introduced by this type of system during maneuvers which involve large changes in flight condition, for example, a low altitude bombing (LAB) maneuver.

Trial-and-error type of flight test investigations revealed that more success in avoiding a P.I.O. maneuver could be realized if mechanisms were employed which produce non-linear stick force gradients about trim and by incorporating stick dampers, etc. in conjunction with the stick-control gearing ratio mechanism. In this instance, we are actually varying the ratio of the dynamic (anticipatory) to steady state stick force cues. In fact, the elementary observation has been made that P.I.O. maneuvers can be avoided if the dynamic stick forces are greater than the steady state stick forces. The CAP theory would suggest that the proper transient stick force cue should be a function of airplane angular acceleration. This force cue can be generated either electronically or mechanically (double bob weight). The value of this particular technique is supported by the pilot observations reported during the investigation of Reference (9). For this technique, we probably have a stick force ratio index which is similar to the CAP index, i.e., a desired ratio of initial to final (steady state) stick force.

It should be noted that supplying transient and steady state stick force cues are basically inefficient and limiting in the amount of alleviation to be realized for airframes that exceed the upper limit of the CAP (control sensitivity). These stick force cues are more effective in improving the acceptability of an airframe which falls below the lower limit of the CAP value (in this instance the stick force cue substitutes for the non-existent vestibular cue).

B. AUTOMATIC FLIGHT CONTROL SYSTEM

Instead of resorting to stick force cues, the acceptable CAP values may be artificially produced such that a pilot can continue to control the airplane through the "seat of his pants". The inherently deficient airframe can simulate the desired CAP characteristics through the use of an automatic flight control system (AFCS). As discussed below, this can be accomplished by modifying the apparant natural frequency of the vehicle and/or by altering the pilot-AFCS-airframe dynamic response characteristics.

The prime function of specifying a desirable damping ratio (ζ = .4 to .7) in the overall longitudinal handling qualities criteria is in respect to the minimum pilot effort required in cancelling the response of the aircraft to unwanted external or self-induced disturbances. Precision controllability cannot be accomplished on an aircraft deficient in the CAP by increasing the damping ratio, per se, although the pilot tolerance of such a deficient airframe will be

influenced, to a small degree, for the above stated reason.

The CAP (or natural frequency as discussed in Section III D), however, is a function of the damping in pitch, $C_{m_{\dot{\theta}}}$, as shown in Eq. (3). Normally this is not an important contribution to the CAP if the damping is natural. When a high pass filter is not incorporated in a stability augmentation system network, an appreciable increase in the value of the CAP is realized for aircraft possessing low levels of static stability. The CAP or natural frequency can, of course, be directly augmented by incorporating a network which changes the apparant static margin of the airframe.

It is the authors opinion that the desired CAP may be more efficiently achieved by incorporating a very simple angular acceleration shaping network in an existing AFCS. This precision control loop (PCL) would be activated upon application of a specified stick force and in this manner only the basic airframe transient maneuvering response characteristics would be modified. The sign and magnitude of the control deflection signal generated by the PCL would depend on the magnitude of the inherent airframe CAP. Therefore, by directly operating on the man-machine precision control environment as prescribed by the CAP concept, precision controllability may be simply achieved for very high performance modern vehicle configurations with no degradation of desirable (for example, low gust response) airframe characteristics.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. A control anticipation parameter (CAP) is presented herein which relates the quantities which are involved in the man-machine precision control mechanism. This index is a ratio of the instantaneous angular pitching acceleration generated per unit of steady state load factor.

2. There is a range of CAP values which are associated with good handling qualities. For this range, the pilot can perform as a tight (high gain) controller since he is able to fly "by the seat of his pants" employing the cristae ampullaris and otoliths of the inner-ear to sense angular and normal accelerations, respectively.

3. The acceptable range of CAP values is bracketed by a lower and upper limit. Below the lower limit, the desired ultimate response (change in flight path) of the airplane cannot be anticipated by the pilot since a perceptible level of the anticipatory cue (angular pitching acceleration) is not present. Whereas, the upper limit may be indicative of a horrendous anticipatory signal for a relatively small change in flight path.

4. It appears that good handling qualities are realized for CAP values above 25 degrees per second squared per g and that the lower critical value is approximately 15 degrees per second squared per g.

5. When the inherent aircraft CAP value falls below the critical value, the pilot may accomplish a precision task by using a control technique which involves a sinusoidal pumping of the control surface.

6. The CAP can be approximately expressed by the ratio of ω_n^2 to n_α for specification purposes.

7. It is recommended that the following handling qualities studies and investigations be pursued in order to specify the required airframe precision control characteristics.

    a. The CAP range and the corresponding criterion (ω_n^2 / n_α) associated with good precision control handling qualities should be experimentally determined employing a variable stability

research aircraft.

b. An analytical study should be conducted to determine the proper mechanism for generating the transient stick force cue as a function of the airframe angular acceleration. The desired ratio of this force to the steady state stick force as well as the degree to which this stick force cue technique can be substituted for a basically deficient airframe should then be experimentally determined.

c. The most efficient technique for artificially simulating the desired CAP characteristics on an inherently deficient airframe should be analytically determined.

APPENDIX

LONGITUDINAL CONTROL SURFACE PUMPING

The longitudinal control surface is rapidly pumped during the last few seconds of a landing on many fighter airplanes; the amplitude and rate of the pumping motion varying with airplane design. Since the maximum control surface rate requirement imposed on the normal and emergency control systems is dictated by the control pumping action encountered in the landing phase of the mission, it was deemed advisable to determine the physical significance for this observed phenomenon.

A. ANALYSIS

The rapid pumping of the horizontal control surface occurred only during the last five seconds of the landing. At no time was the control pumped when practice landings were performed a great distance above the ground. It is, therefore, reasonable to assume that the pilot seeks additional information as the airplane approaches the ground and that this information is obtained as a result of pumping the control.

Flight test records of stick and control deflection during landing flare-outs showed the pilot induced pumping motion to be closely simulated by a sinusoidal input superimposed on a ramp input (see Figure A-1). It was thought, therefore, that the information the pilot sought by pumping the control could be directly determined by examining the frequency response characteristics of some airplanes that are pumped.

The airframe frequency response characteristics in $\ddot{\theta}$, $\dot{\theta}$, and $\dot{\gamma}$ to horizontal control inputs were calculated for the F-84E, F-84F (elevator), F-84F (all-moveable horizontal tail) and F-105, using the following transfer functions:

$$\frac{\dot{\theta}}{\delta} = \frac{K_{\theta}(TP + 1)}{(P^2/\omega_n^2 + 2\zeta P/\omega_n + 1)} \qquad \text{Eq. (A-1)}$$

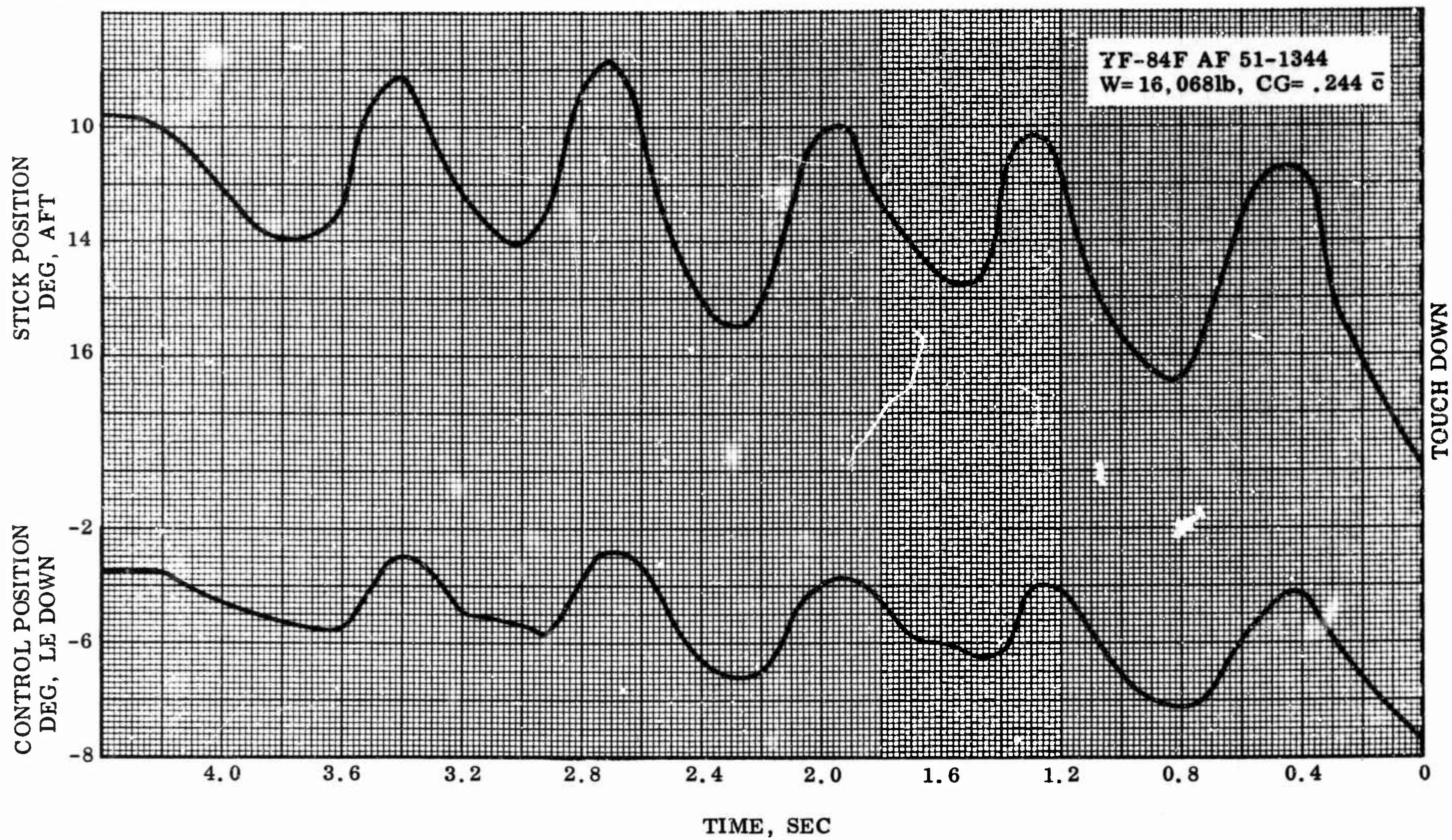

FIG. A-1 TIME HISTORY OF LANDING FLARE OUT

$$\frac{\dot{\gamma}}{\delta} = \frac{K_{\gamma}(T_1 P + 1) \quad (T_2 P + 1)}{(P^2/\omega_n{}^2 + 2\zeta P/\omega_n + 1)} \qquad \text{Eq. (A-2)}$$

$$\frac{\ddot{\theta}}{\delta} = P \frac{\dot{\theta}}{\delta} \qquad \text{Eq. (A-3)}$$

where

$$K_{\theta} = K_{\gamma} = \frac{C_{L_\alpha} C_{m_\delta} - C_{m_\alpha} C_{L_\delta}}{-C_{m_\alpha} \frac{WV}{gqS} - \frac{\bar{c}}{2V} C_{L_\alpha} C_{m_{\dot{\theta}}}} \qquad \text{Eq. (A-4)}$$

$$T = \frac{\frac{WV}{gqS} C_{m_\delta} - \frac{\bar{c}}{2V} C_{m_{\dot{\alpha}}} C_{L_\delta}}{C_{L_\alpha} C_{m_\delta} - C_{m_\alpha} C_{L_\delta}} \qquad \text{Eq. (A-5)}$$

$$\omega_n{}^2 = \frac{-C_{m_\alpha} \frac{WV}{gqS} - \frac{\bar{c}}{2V} C_{L_\alpha} C_{m_{\dot{\theta}}}}{\left(\frac{I_Y}{qS\bar{c}}\right) \left(\frac{WV}{gqS}\right)} \qquad \text{Eq. (A-6)}$$

$$\zeta = \frac{\frac{I_Y}{q\bar{c}S} C_{L_\alpha} - \left(\frac{\bar{c}}{2V}\right)\left(\frac{WV}{gqS}\right)\left(C_{m_{\dot{\alpha}}} + C_{m_{\dot{\theta}}}\right)}{2\omega_n \left(\frac{I_Y}{qS\bar{c}}\right)\left(\frac{WV}{gqS}\right)} \qquad \text{Eq. (A-7)}$$

$$(T_1 \; P + 1) \;\; (T_2 \; P + 1) \;\; = \;\; aP^2 + bP + 1 \qquad \text{Eq. (A-8)}$$

where

$$\frac{b}{a} = \frac{-\dfrac{\bar{c}}{2V}\left(C_{m_{\dot{\alpha}}} + C_{m_{\dot{\theta}}}\right)}{\dfrac{I_Y}{q\,\bar{c}\,S}} \qquad \text{Eq. (A-9)}$$

$$\frac{1}{a} = \frac{C_{m_{\delta}} \; C_{L_{\alpha}} - C_{m_{\alpha}} \; C_{L_{\delta}}}{C_{L_{\delta}} \qquad \dfrac{I_Y}{q\,\bar{c}\,S}} \qquad \text{Eq. (A-10)}$$

The calculated values for the transfer function coefficients for the airplanes presented are:

	$^1/_T$ rad./sec.	$^1/_{T_1}$ rad./sec.	$^1/_{T_2}$ rad./sec.	ω_n rad./sec.	ζ	$-K_\theta$ ratio	$-K_\theta$ db
F-105	.424	3.78	-3.47	1.049	.363	.819	-1.74
F-84F	.524	6.10	-5.21	1.581	.458	1.042	0.40
F-84F(elev).	526	6.29	-5.40	1.581	.458	.529	-5.54
F-84E	.842	8.73	-7.52	1.590	.670	2.190	6.80

B. DISCUSSION

The airframe frequency response characteristics in $\ddot{\theta}$, $\dot{\theta}$, and $\dot{\gamma}$ to the angular frequency forcing function of the control surface are given in Figures

A-2, A-3, and A-4, respectively. The average frequency at which the pilot pumped the control is also indicated in these figures. (The pumped frequency for the F-105, however, was obtained after this study was conducted.)

These data show that the control is pumped by the pilot at a frequency which is considerably above the natural frequency of the airframe. At these pumping frequencies, the airplane response in $\dot{\gamma}$ is negligible whereas the response in $\ddot{\theta}$ is close to the maximum value attainable. A minimum phase shift (in the order of 10 degrees or less) also is realized between $\ddot{\theta}$ and the control surface deflection at these high pumping frequencies. If the control system has acceptable resolution, the control stick deflection is correspondingly in phase with the resultant $\ddot{\theta}$. The point to be emphasized is that higher magnitudes of $\dot{\gamma}$ and $\dot{\theta}$ per unit control input could be obtained which would also be more in phase with the control input at considerably lower pumping frequencies than those employed by the pilot. It appears, therefore, that the pilot desires to excite the airplane in pitch, which he accomplishes by sensing the angular pitching acceleration without disturbing the airplane flight path.

Based on the data presented herein, it appears that the control of a given design will be pumped at the frequency which approaches the minimum attainable phase shift between angular acceleration and the corresponding forcing function. If the amplitude ratio, $|\ddot{\theta}/\delta|$, is calculated for this frequency and divided by the threshold of perception of angular acceleration, the amplitude of the pumping motion can also be predicted.

The threshold of perception for a human is shown in Reference (7) to be a function of the time duration the subject experiences the stimulus, i.e., the shorter the exposure, the higher the threshold value. Unfortuantely, no experimentally determined threshold values are available for the short time periods involved in the pumping flight maneuver. If one multiplies the amplitude ratio by the average control amplitude measured in flight, a $\ddot{\theta}$ is generated which must be at least a detectable (threshold) value. For instance, for the configurations presented herein:

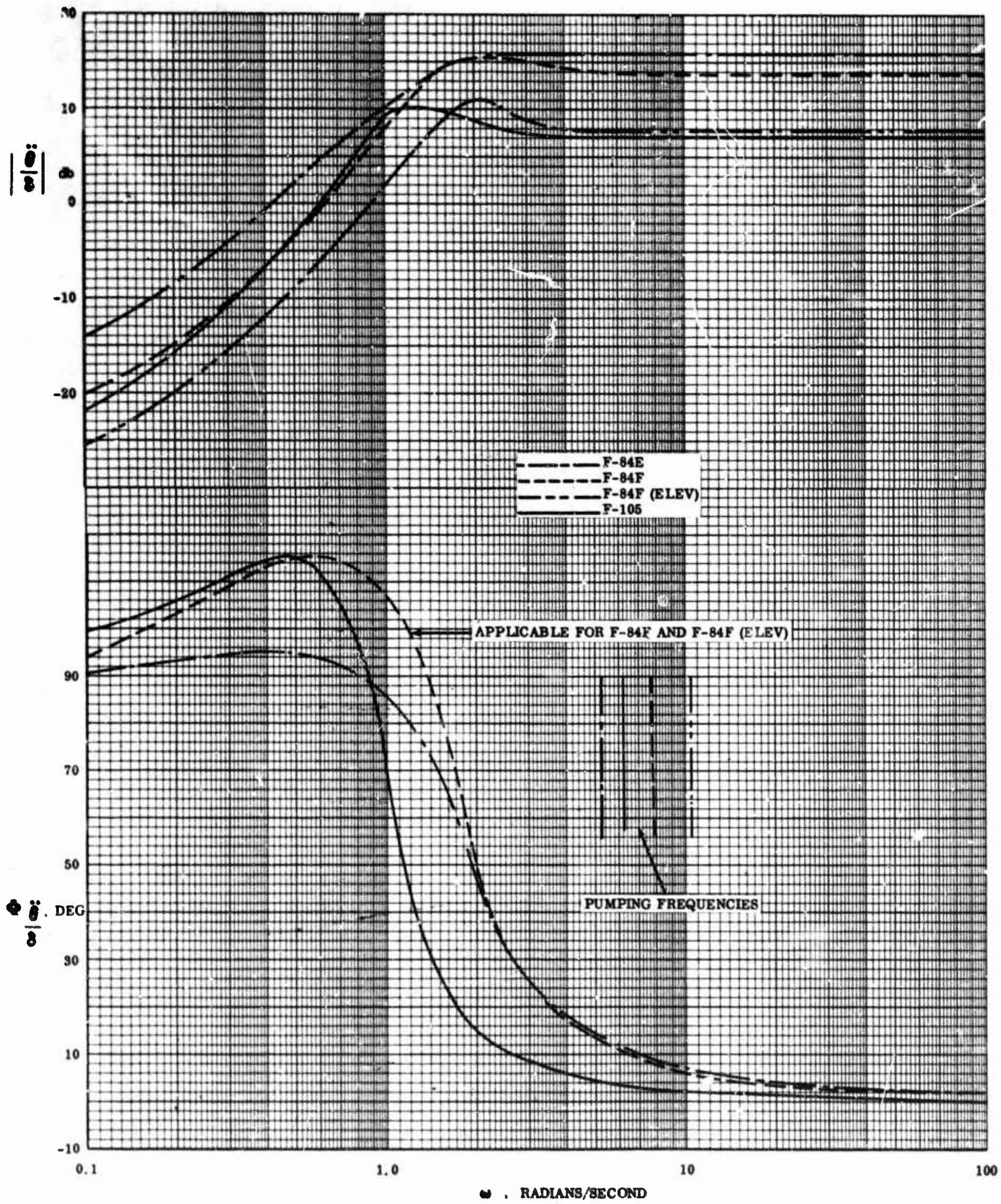

FIG. A-2 FREQUENCY RESPONSE IN ANGULAR ACCELERATION FOR VARIOUS AIRCRAFT IN THE LANDING CONFIGURATION

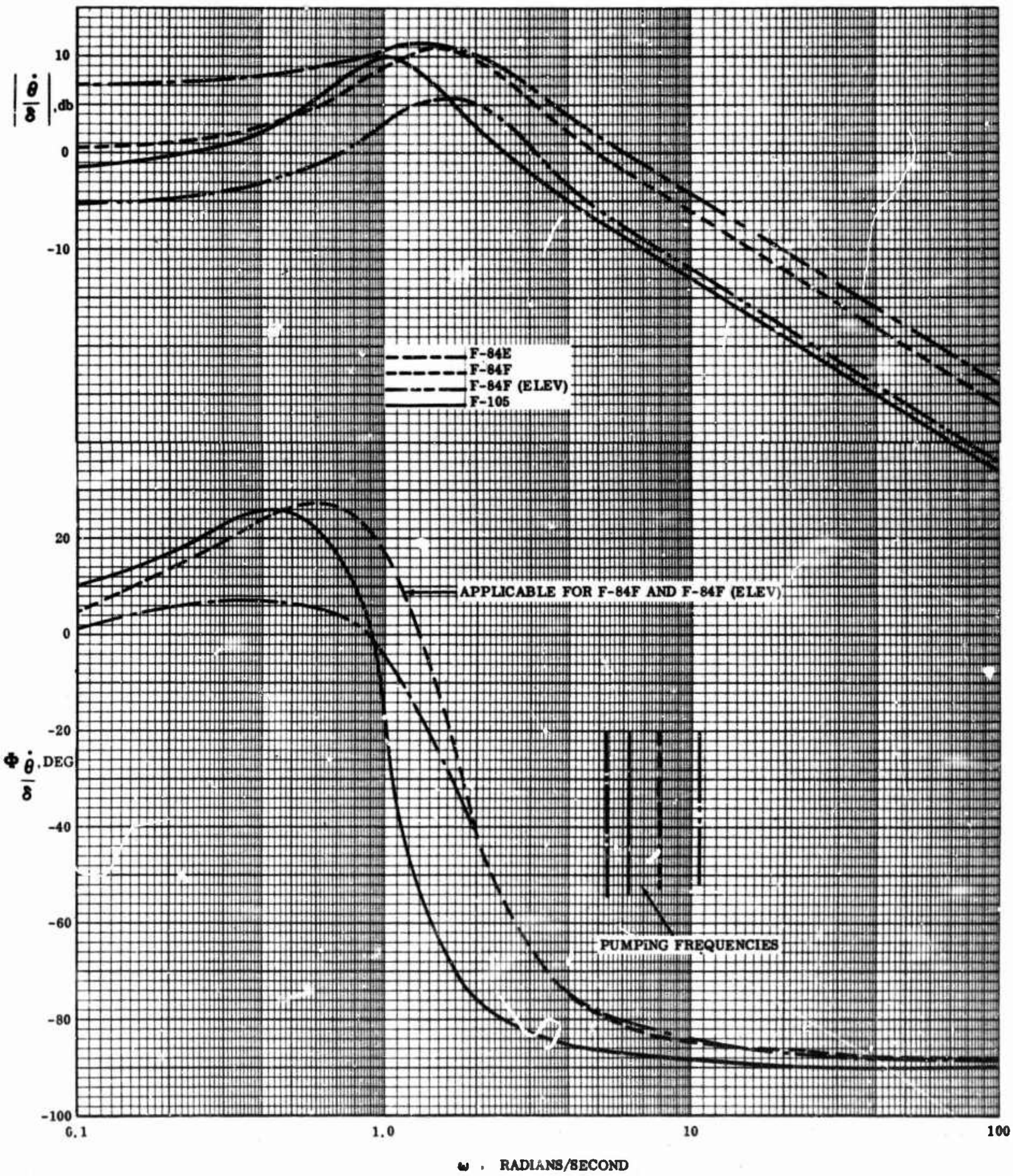

FIG. A-3 FREQUENCY RESPONSE IN ANGULAR VELOCITY FOR VARIOUS AIRCRAFT IN THE LANDING CONFIGURATION

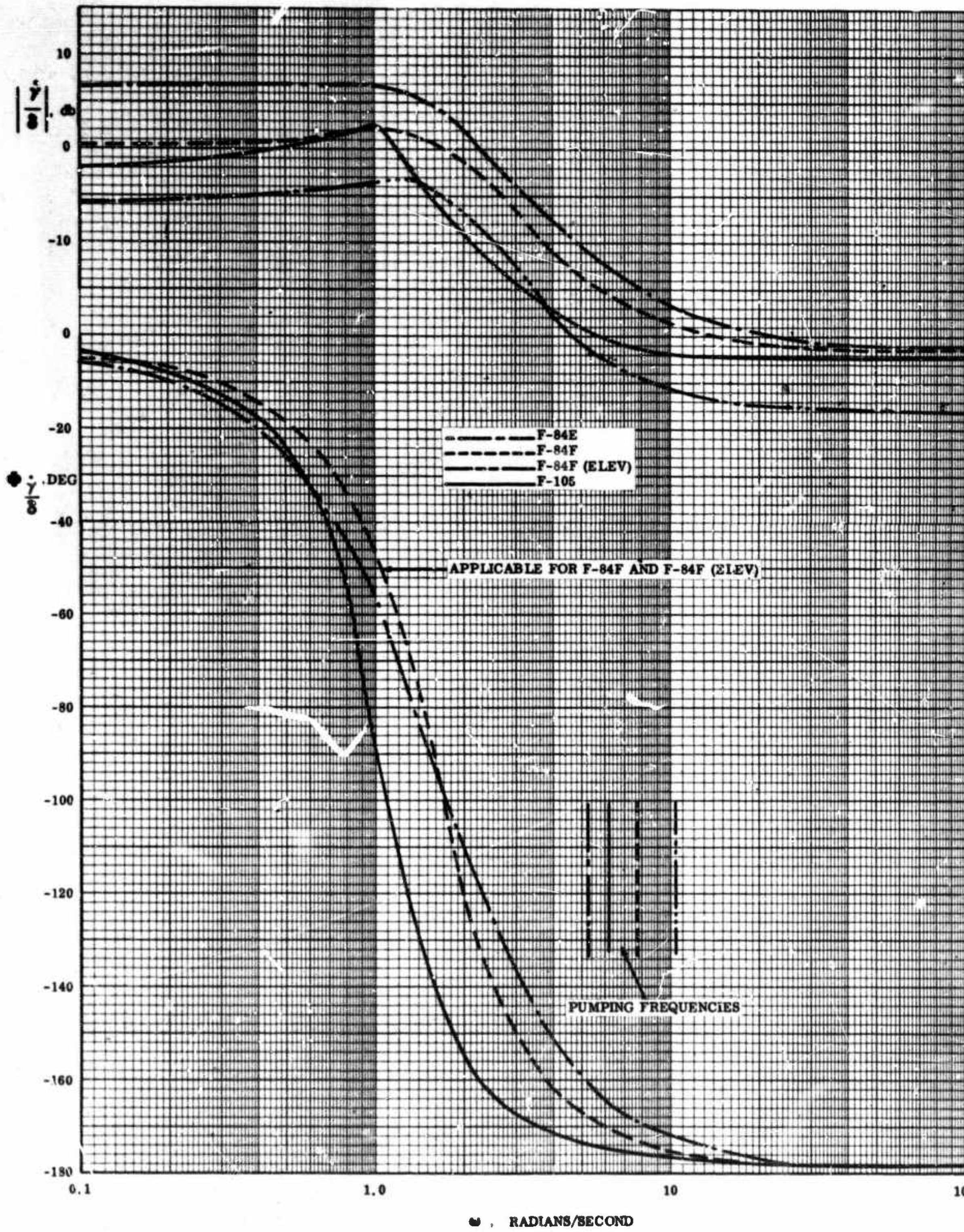

FIG. A-4 FREQUENCY RESPONSE IN RATE OF CHANGE OF FLIGHT PATH ANGLE FOR VARIOUS AIRCRAFT IN LANDING CONFIGURATION

	Average Control Amplitude degrees	$\left\lvert \frac{\ddot{\theta}}{\delta} \right\rvert$ per sec.^{2}	$\ddot{\theta}$ deg./sec.^{2}
F-105	$\pm$ 2.9	2.3	6.7
F-84F	$\pm$ 1.3	5.1	6.6
F-84F(elev.)	$\pm$ 2.4	2.5	6.0
F-84E	$\pm$ 1.0	6.4	6.4

From the above data, it appears that this threshold value is approximately 6.5 degrees per second squared. This threshold value is considered valid since it is based on flight determined data involving various pilots flying airplanes of different designs.

C. CONCLUDING REMARKS

It should be appreciated that this study was conducted using recorded flight test data which were obtained by a considerable number of pilots flying different aircraft over a period of many years. In no instance was the flight test recordings obtained specifically and systematically for the investigation of the control surface pumping phenomenon. Also, the computed frequency response characteristics are within the accuracy of the estimated aerodynamic coefficients and the flight test noted mass characteristics (center of gravity, weight, and inertia). In light of this non-research type of information, the consistency of the observations derived from the analysis presented herein is considered quite remarkable.

Also, based on this study, it was predicted during the design phase of the F-105 that the control surface would be pumped on this aircraft at a frequency above 4 radians per second and at an amplitude of $\pm$ 2.8 degrees. It was also recommended that allowance be made for by-passing the stick damper in the landing mode so as not to restrict the pilot in his pumping action. The experimental flight article was pumped at a frequency of 6.29 radians per second and at an amplitude of $\pm$ 2.9 degrees. The pilots also concurred with the recommendation for by-passing the stick damper.

The consistency of the study results and the ability to predict the control pumping characteristics of an aircraft during the preliminary design phase are taken as an indication of the overall correctness of the following conclusions.

1. When the pilot pumped the control during a precision task, he attempted to excite and sensed an airframe response in angular acceleration.

2. The pilot pumped the control surface at frequencies appreciably above the natural frequency of the airframe which resulted in obtaining

   a) the maximum attainable angular acceleration per unit control input

   b) the minimum attainable phase shift between the control input and corresponding pitching acceleration

   c) a negligible change in flight path angle (normal acceleration) and a considerably attentuated response in pitching velocity

3. The threshold of perception of pitching acceleration is approximately 6.5 degrees per second squared for the short time period the pilot is subjected to this stimulus during the pumping maneuver.

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13. ABSTRACT

This paper discusses the overall subject of precise flight path control. A unifying precision control theory is presented and a control anticipation parameter is developed which relates the quantities that are involved in the man-machine precision control mechanism. A critical value for this parameter is suggested, based on experimental results, and is discussed in relation to pilot adaptability as reflected under the topics of control technique (control pumping), control function and control task. Also, an associated criterion in terms of aircraft characteristics is developed and techniques for improving the precision controllability of inherently deficient airframes through stick force and automatic flight control systems are discussed. Finally, experimental and analytical investigations are recommended which are deemed necessary for specifying the longitudinal handling qualities of manned vehicles.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Handling Qualities						
Longitudinal short period requirements						
Precise flight path control						
Control anticipation parameter						
Control pumping						

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